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SQUID applications in the SNS nEDM Experiment

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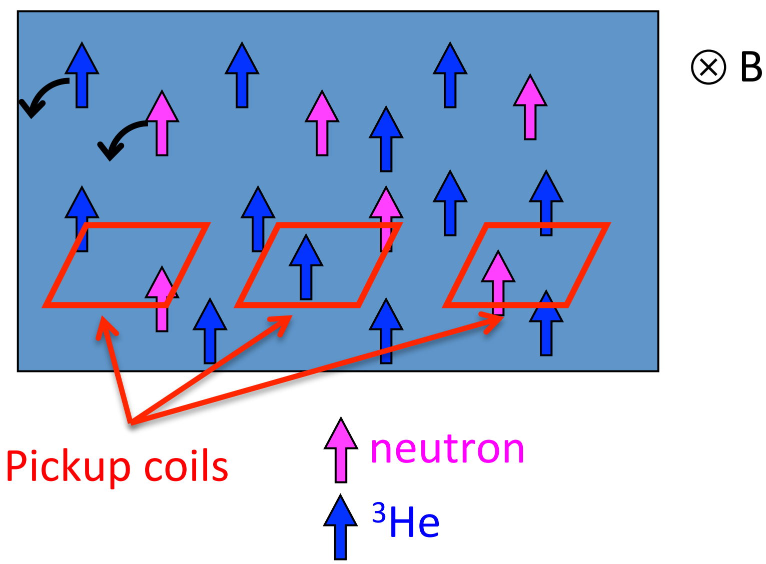
Contents:

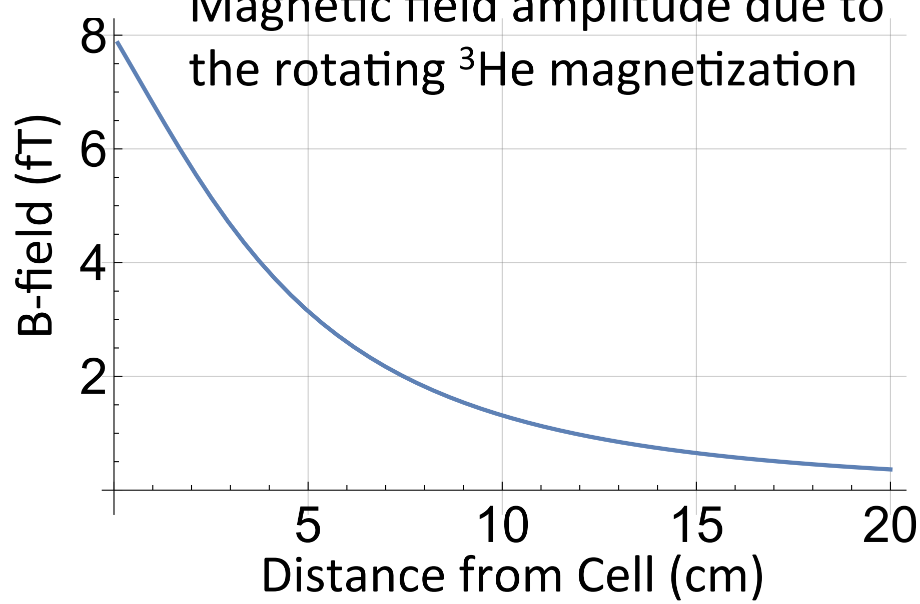
- Role of SQUIDs in nEDM@SNS
- DC SQUID principles
- Low-noise detection of ^{3}He magnetization
- Implementation into nEDM@SNS
- Tests with a candidate SQUID

Challenges of the worldwide experimental search for the electric dipole moment of the neutron, 2-6 November 2014, Ascona, Switzerland

Free Precession Method

The ^{3}He magnetization precession is directly detected (n+^{3}He scintillation events effect spin analysis, as with dressed spin).





^{3}He concentration is chosen to maximize EDM statistical sensitivity based on scintillation events.

- Low concentration ➔ small BR for capture events, few scintillation events
- High concentration ➔ short storage time
- $\rho_{3He} \approx 2\times10^{12}$/cc is optimal if long storage time.

^{3}He Co-magnetometer Readout

$$d_n = \frac{\hbar}{2E}\left[2\pi(f_s^{\uparrow} - f_s^{\downarrow}) - \underbrace{\boxed{\frac{(\gamma_3 - \gamma_n)}{\gamma_3}}}_{=0.1} 2\pi(f_3^{\uparrow} - f_3^{\downarrow})\right]$$

scintillation signals ~10 Hz

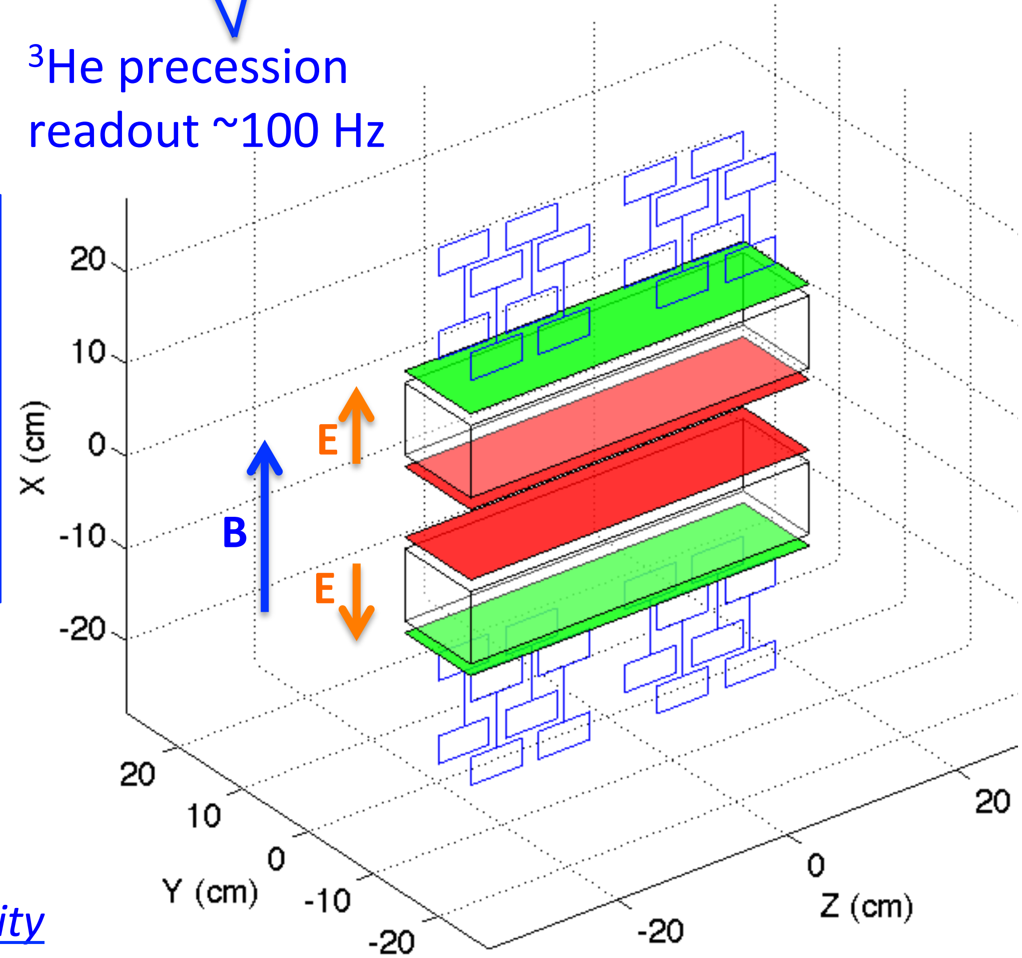
^{3}He precession readout ~100 Hz

To match statistical error of scintillation signal, we need

$$\delta f_3 \approx 26\mu\text{Hz}$$

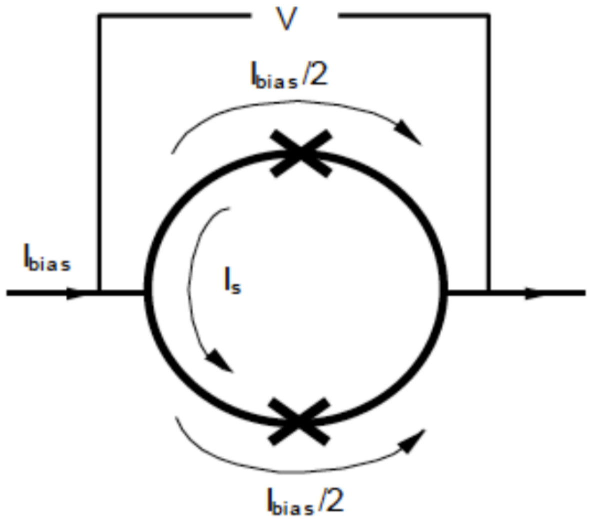
per 800 s measurement period.

Expected ^{3}He magnetization signal amplitude: 2.3 fT

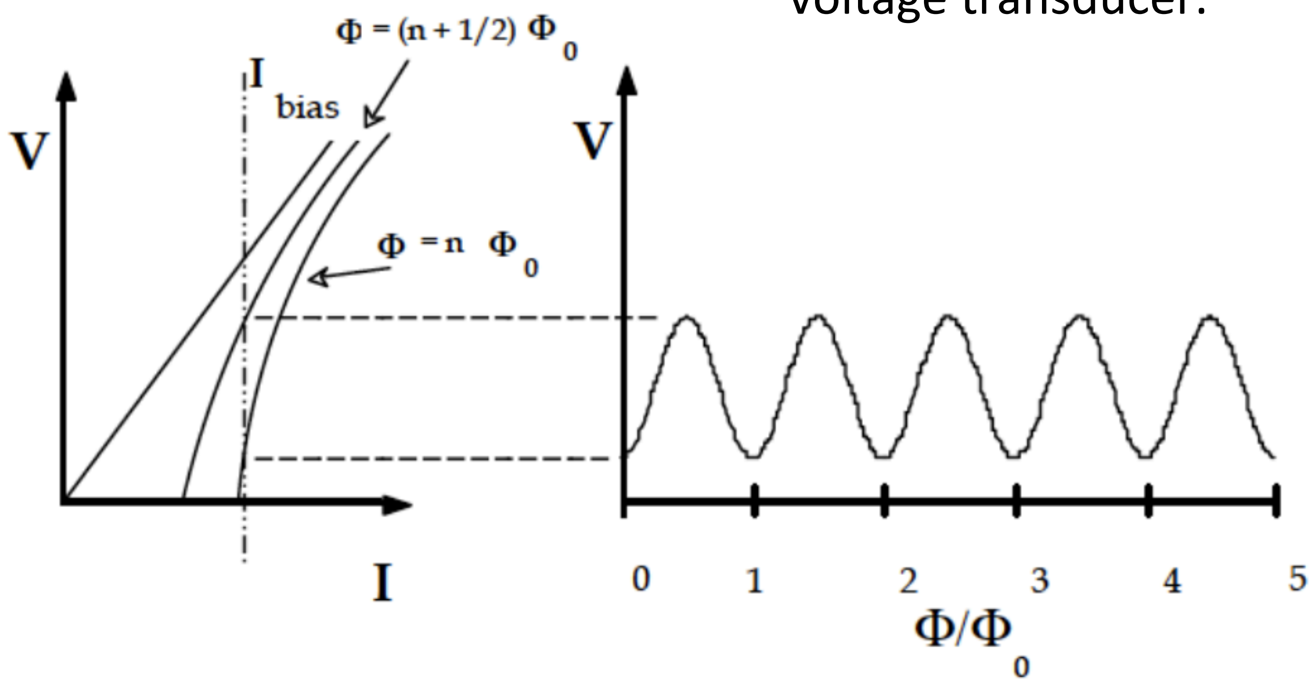


Kim Y. J., Clayton S. M.
IEEE Transactions on Applied Superconductivity **23**, 2500104 (2013).

DC SQUID Principles



- A circulating current opposes any change in applied magnetic flux up to P0/2
- Josephson junctions become resistive when the critical current is exceeded.
- Constant bias current → magnetic flux-to-voltage transducer.



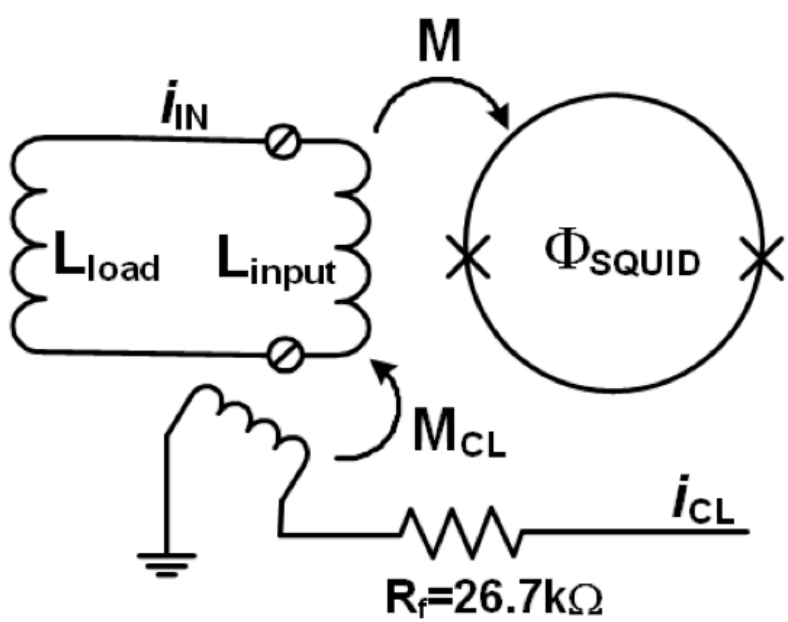
(Figures from Mr. SQUID® User's Guide, STAR Cryoelectronics)

DC SQUID Principles

A pickup loop can be transformer-coupled to the SQUID loop.

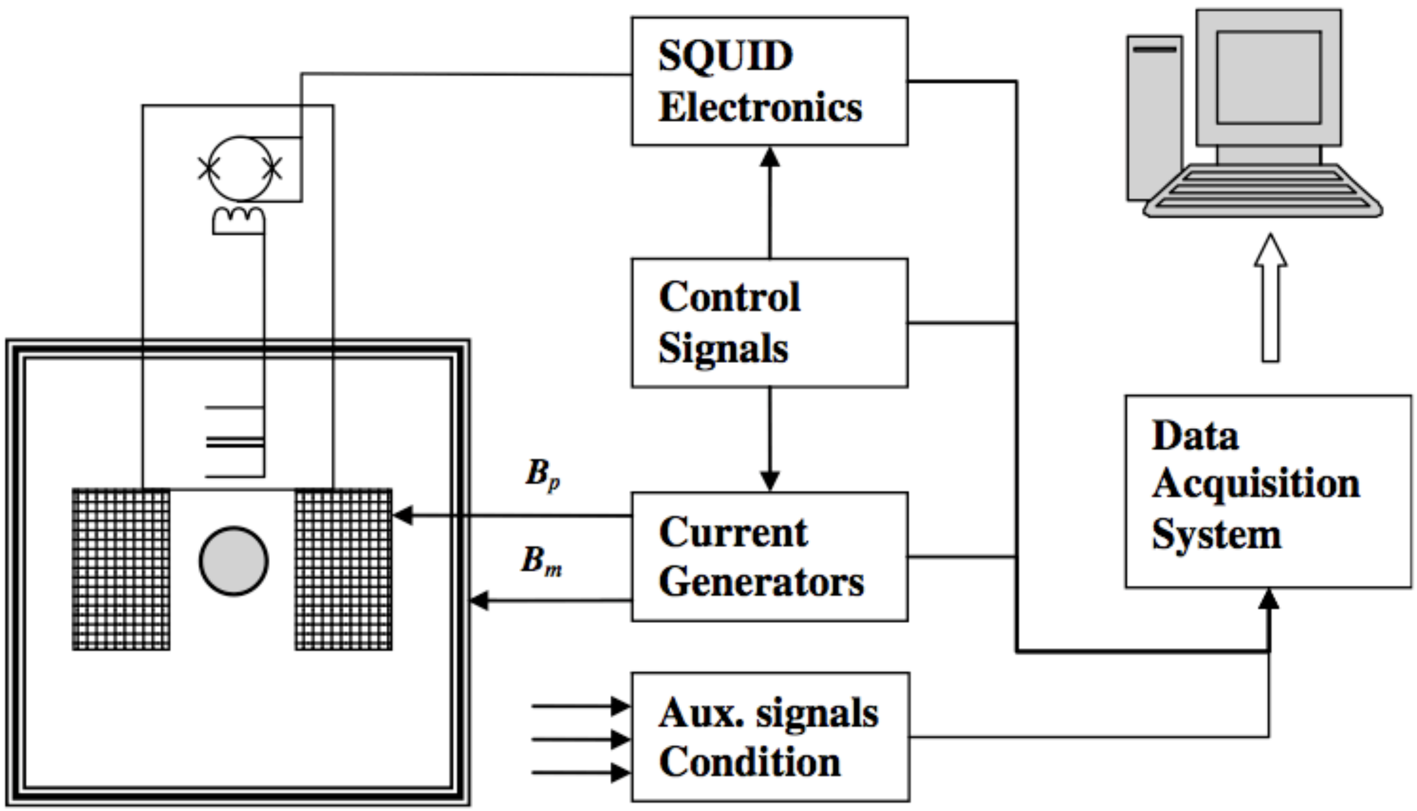
$$\Phi_{SQUID} = \underbrace{\boxed{\frac{M}{L_{pickup} + L_{input} + L_{parasitic}}}}_{\text{~1\% typical}} \Phi_{pickup}$$

External electronics provide feedback/modulation to maintain the same position on the V-Φ curve (feedback can be coupled to the SQUID loop or the input circuit).

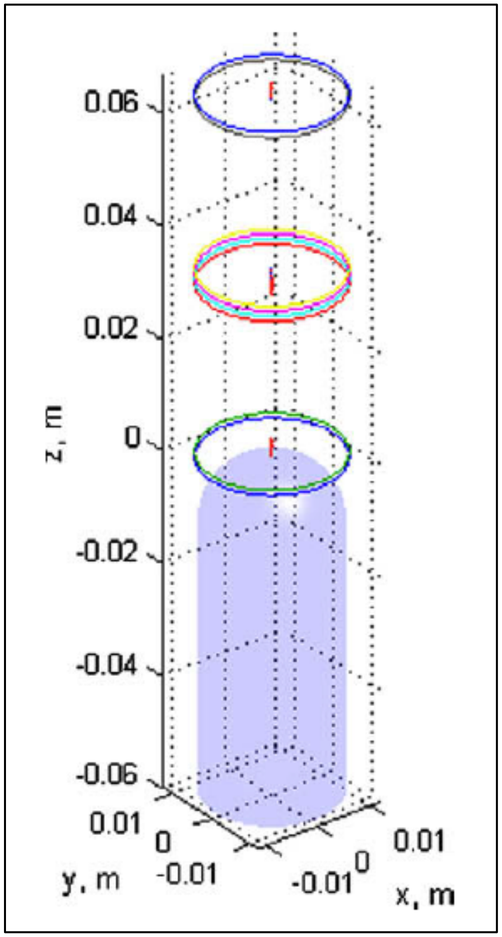


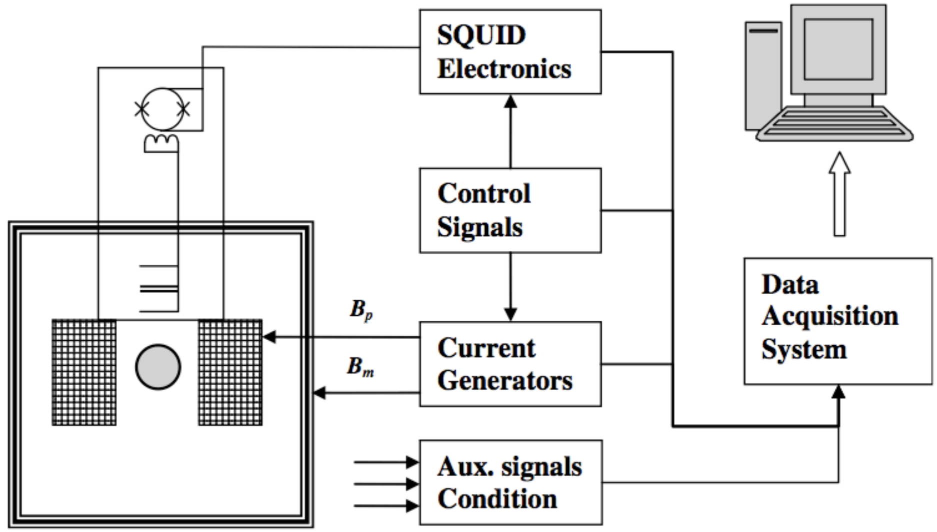
Low-Noise SQUID Operation for ^{3}He Precession Readout

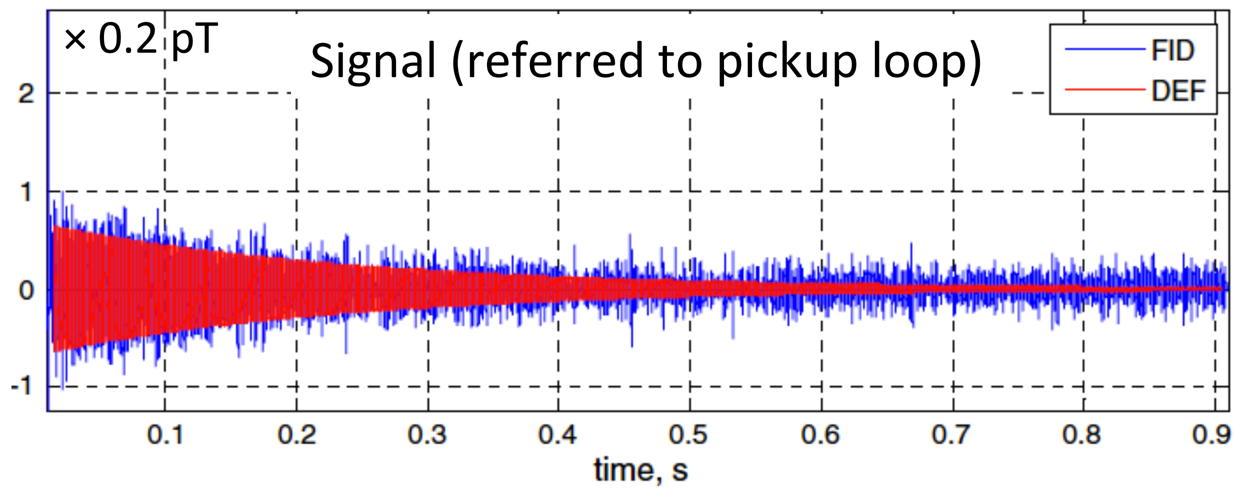
- Proof-of-principle demonstration by LANL magnetometry group
  - I. Savukov et al., Journal of Magnetic Resonance 195 (2008) 129–133.



Low-Noise SQUID Operation for ^{3}He Precession Readout



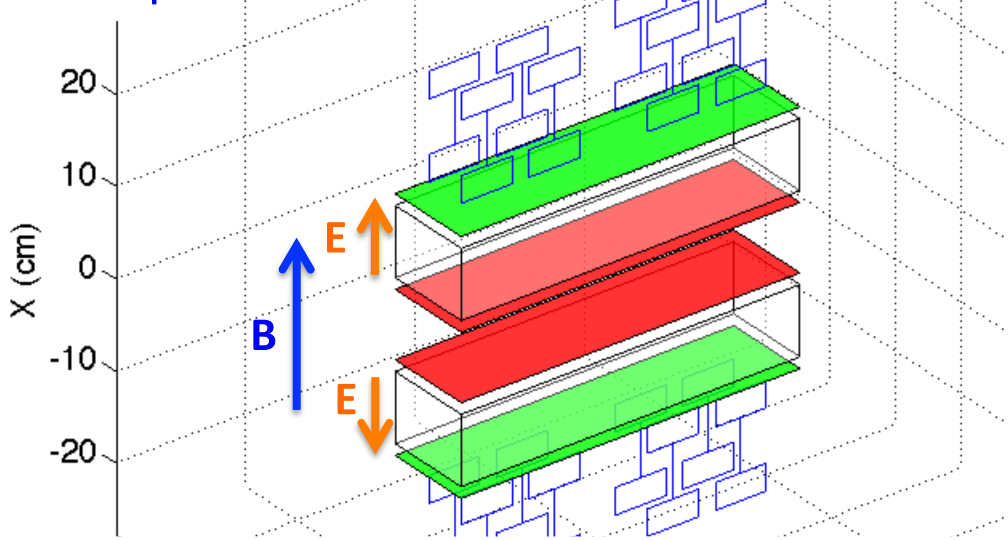


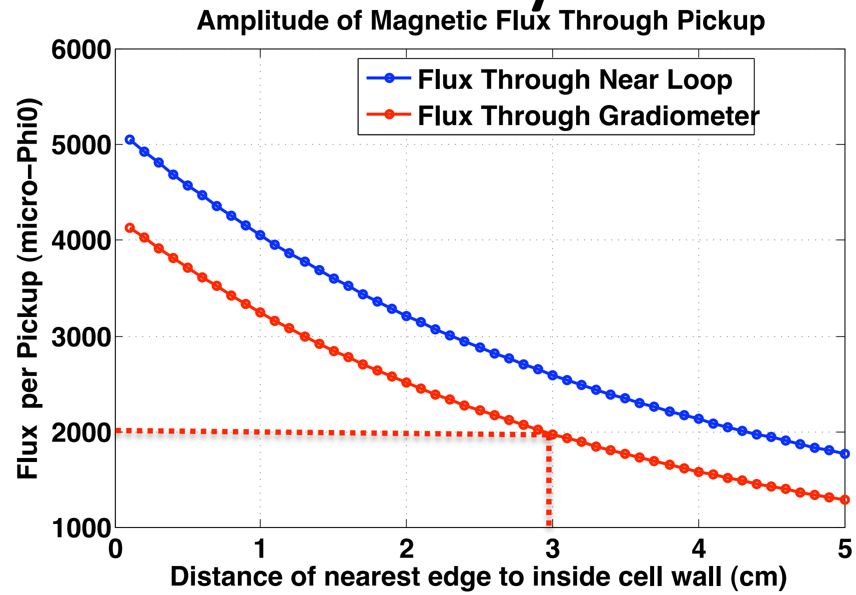


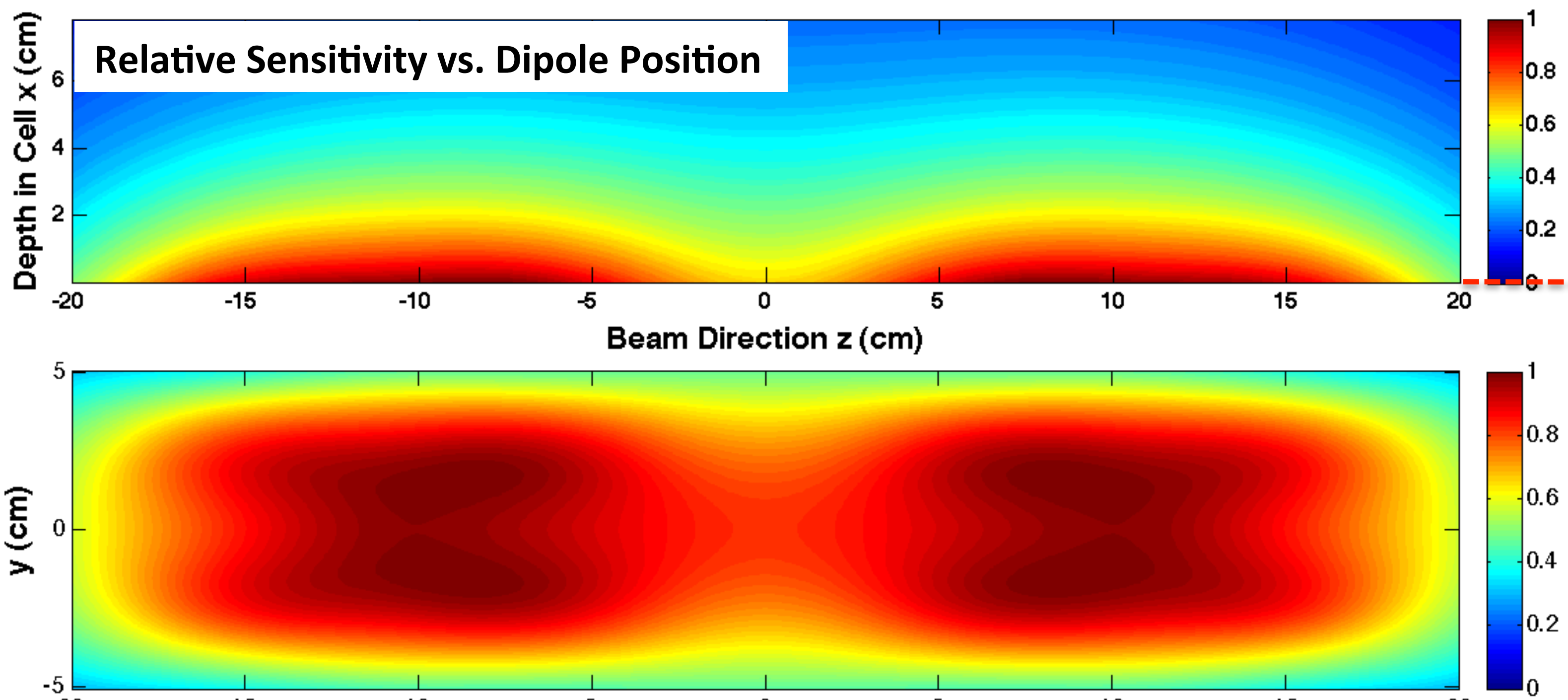
- I. Savukov et al., J. Mag. Resonance 195 (2008) 129–133.
  - Extrapolated to nEDM conditions (smaller signal but longer T_2): δf_3 ~ 3.4 μHz per 500 s measurement (well satisfying δf_3 < 25 μHz needed for nEDM)

Signal through Gradiometer Array

^{3}He precession ~100 Hz

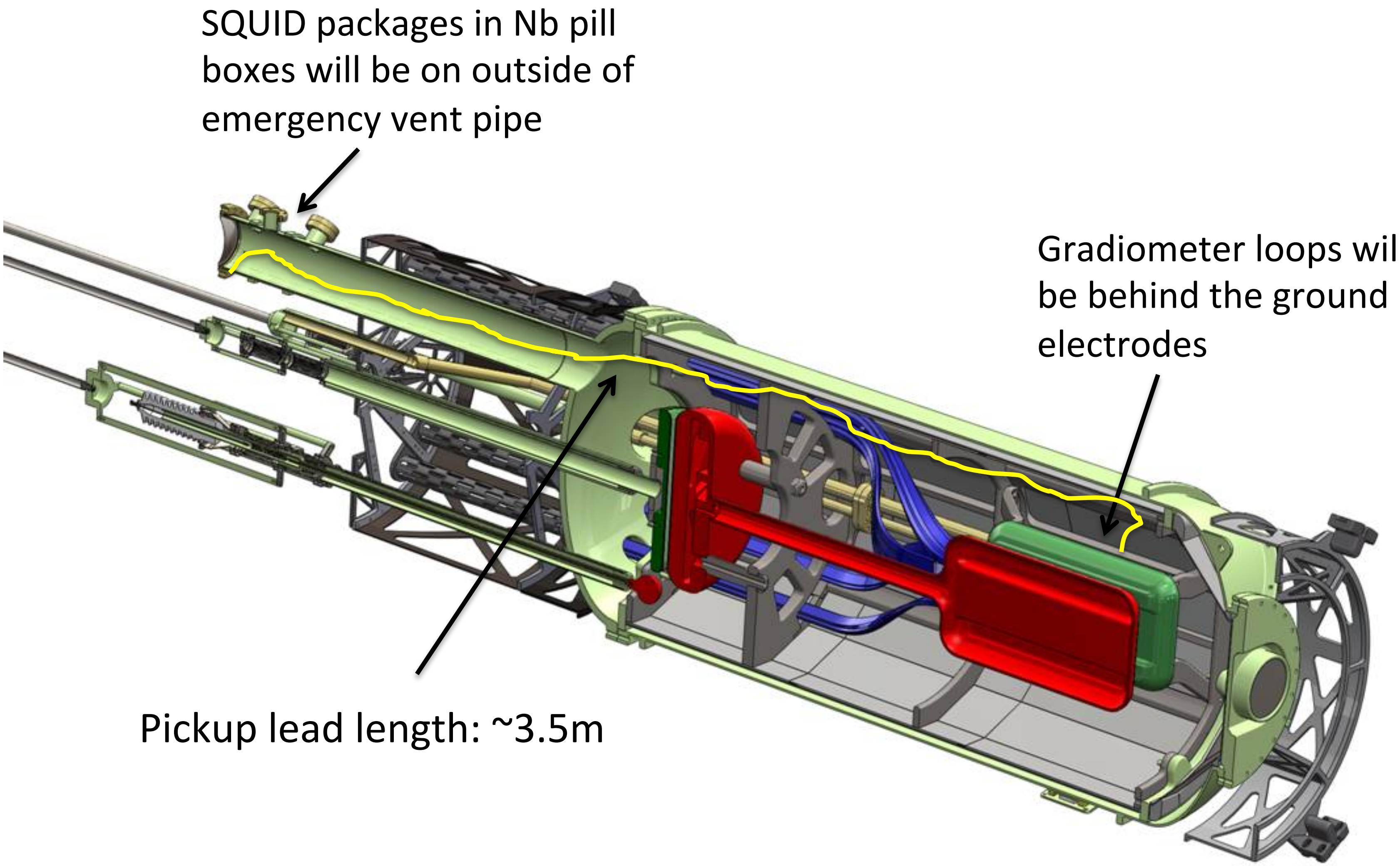






3 cm from edge of pickup

Cutaway View of Central Detector (Old Arrangement)



The reconfigured apparatus (see R. Golub's presentation, this conference) may allow shorter leads, and superconducting end-caps will improve axial shielding.

SQUID Noise Requirement

EDM uncertainty d_n

$$(\delta d_n)^2 = \left(\frac{h}{4E_0}\right)^2 \left\{ 2(\delta\nu_{n3})^2 + \left(\frac{\gamma_n - \gamma_3}{\gamma_3}\right)^2 2(\delta\nu_3)^2 \right\}$$

from capture (light) signal

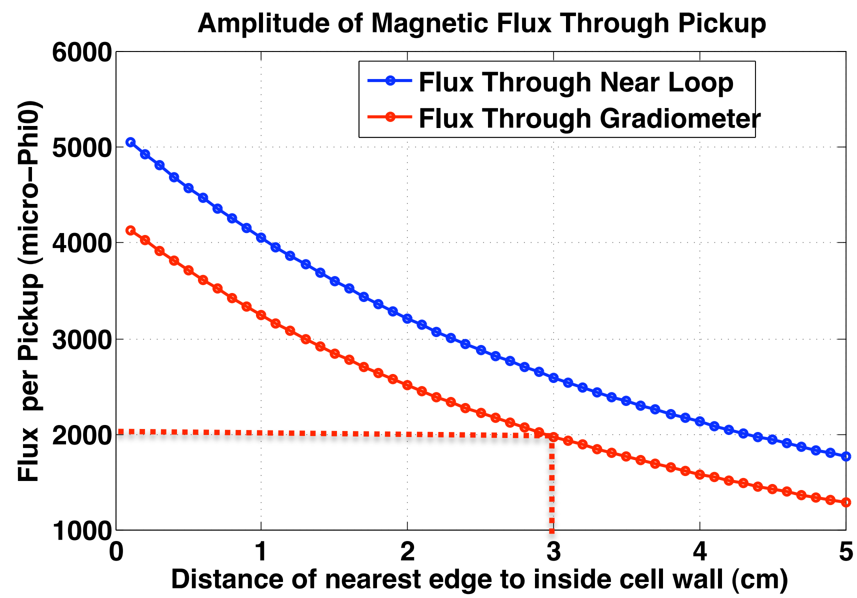
from ^{3}He (SQUID) signal

Noise in SQUID

Chibane et al., *Meas. Sci. Tech., Vol. 6, 671 (1995)*

$$(\delta\nu_3)^2 \approx \left(\frac{N_S}{\Phi_S}\right)^2 \frac{3}{\pi^2 T_{\mathrm{meas}}^3}$$

Signal amplitude in SQUID



- With 3.5-meter leads (1750 nH) to StarCryo SQ2600 (N_S = 4 $\mu\Phi_0$), Φ_S = 10 $\mu\Phi_0$/rtHz and $\delta\nu_3$ = 10 μHz per 800-second measurement period using one pickup/ SQUID only.
- The $\delta\nu_3$ that would match the expected n-capture (ν_{n3}) contribution to the EDM uncertainty is 25 μHz.
- If SQUID noise in each channel is uncorrelated, $\delta\nu_3 \rightarrow \delta\nu_3$/sqrt(8).

The equivalent B-field noise referred to one gradiometer half is 1 fT/rtHz.

What happens when SQUID is exposed to RFI?

SQUID is a “flux to frequency to voltage” converter:

Josephson V→ Frequency ratio 2e/h = 484 MHz/μV

At 1 – 50 μV voltage swing → 0.5 – 25 GHz

Even low-level external RF signal interferes with SQUID internal generation and degrades its noise performances

High-level RFI (1 W radio transmitter at 10 m distance):

- Depressed or even zeroed V-Φ curve
- SQUID can trap flux
- Unpredictable jumps → huge 1/f noise
- Huge amount of “unknown” harmonics
- White noise increased by 10 or more times

Medium-level RFI (can be a microwave oven or RF welding connected to the same power line):

- White noise increased up to 2-3 times
- Some large “unknown” harmonics
- Unacceptably high 1/f noise

Low-level RFI (ULF MRI system in SM218):

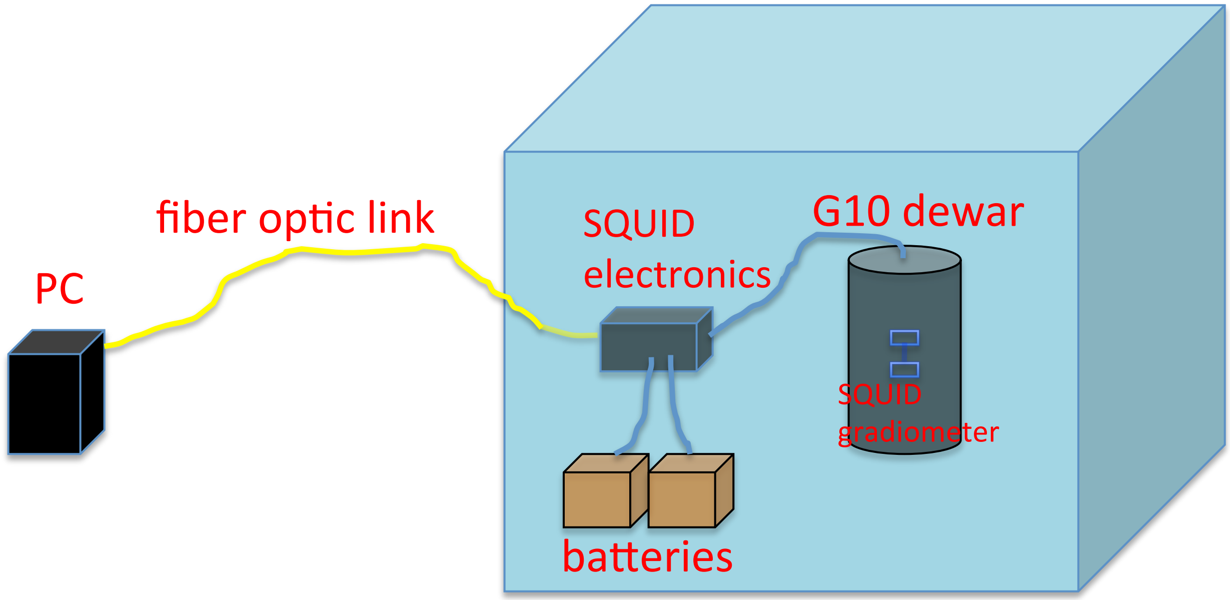
- A few low-level “unknown” harmonics
- Not exactly flat noise below 100 Hz

Slide from Andrei Matlashov, 2007

Implementing SQUIDs into nEDM@SNS

- The nEDM apparatus will be large and complex (see R. Golub's talk, this conference).
- Constraints on the SQUID system:
  - Cannot significantly distort the B-field in the cells.
  - Must be compatible with dressed-spin running (e.g., can't significantly distort the ~1 kHz, ~1 Gauss dressing field).
- Our approach:
  - Locate SQUIDs far away from the cells; connect pickup loops with long, twisted-pair leads (partially in Pb conduit).
  - Battery-power everything within the shielded environment.
  - Avoid conductors penetrating the Faraday cage; fiber-optically isolate electronics.
  - Avoid sources of EMI within the Faraday cage, e.g., switching power supplies.
  - Test candidate SQUID system in mock-up; check EMI compatibility with other electronics; implement SQUIDs into other subsystems' prototype apparatuses where indicated.

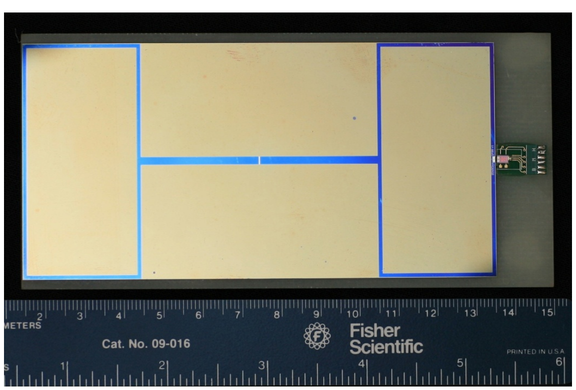
SQUID Test Stand at LANL

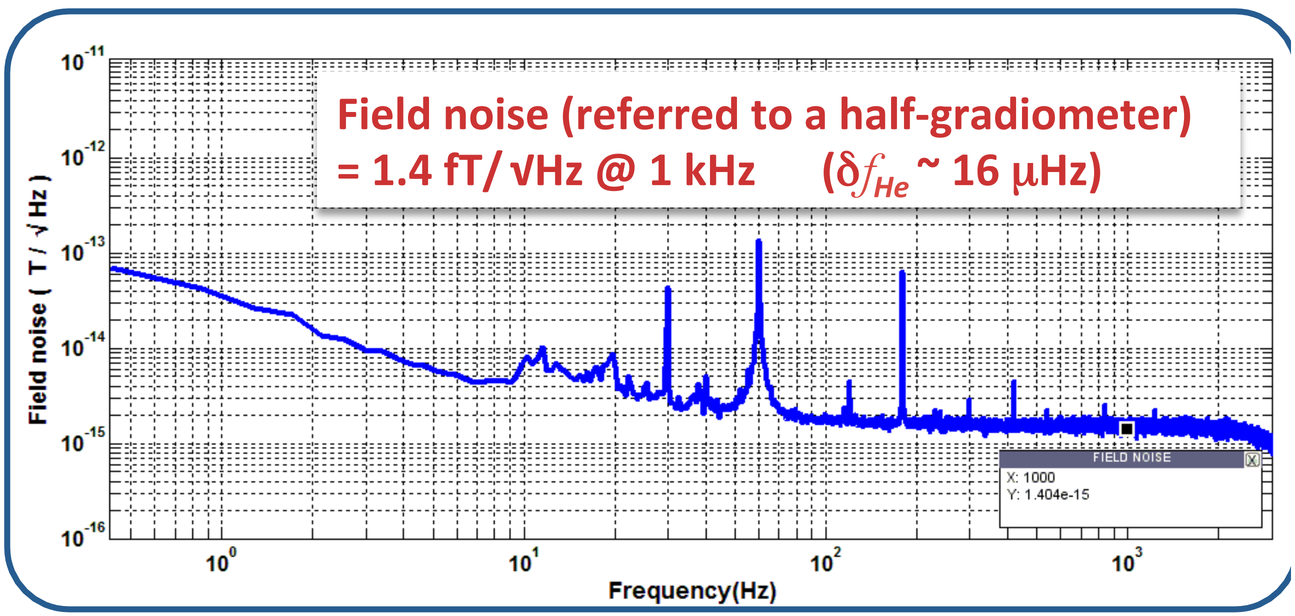


2-layer magnetically shielded room

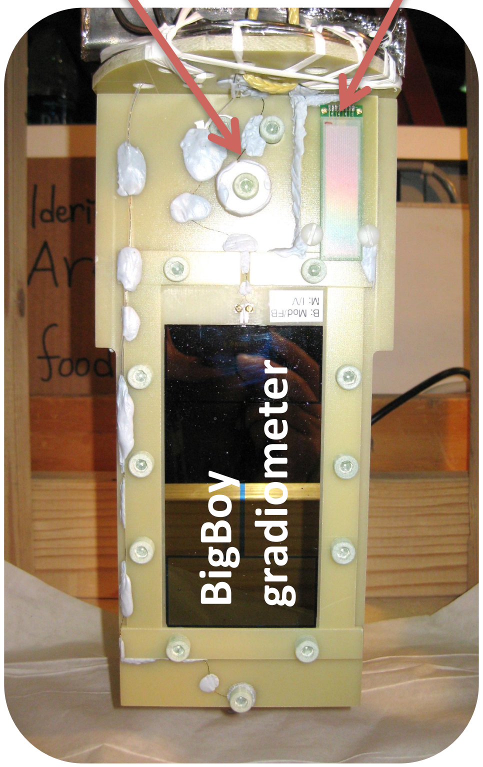
- Residual field < 0.1 mG
- Shielding factor ~10^4 at a few Hz.

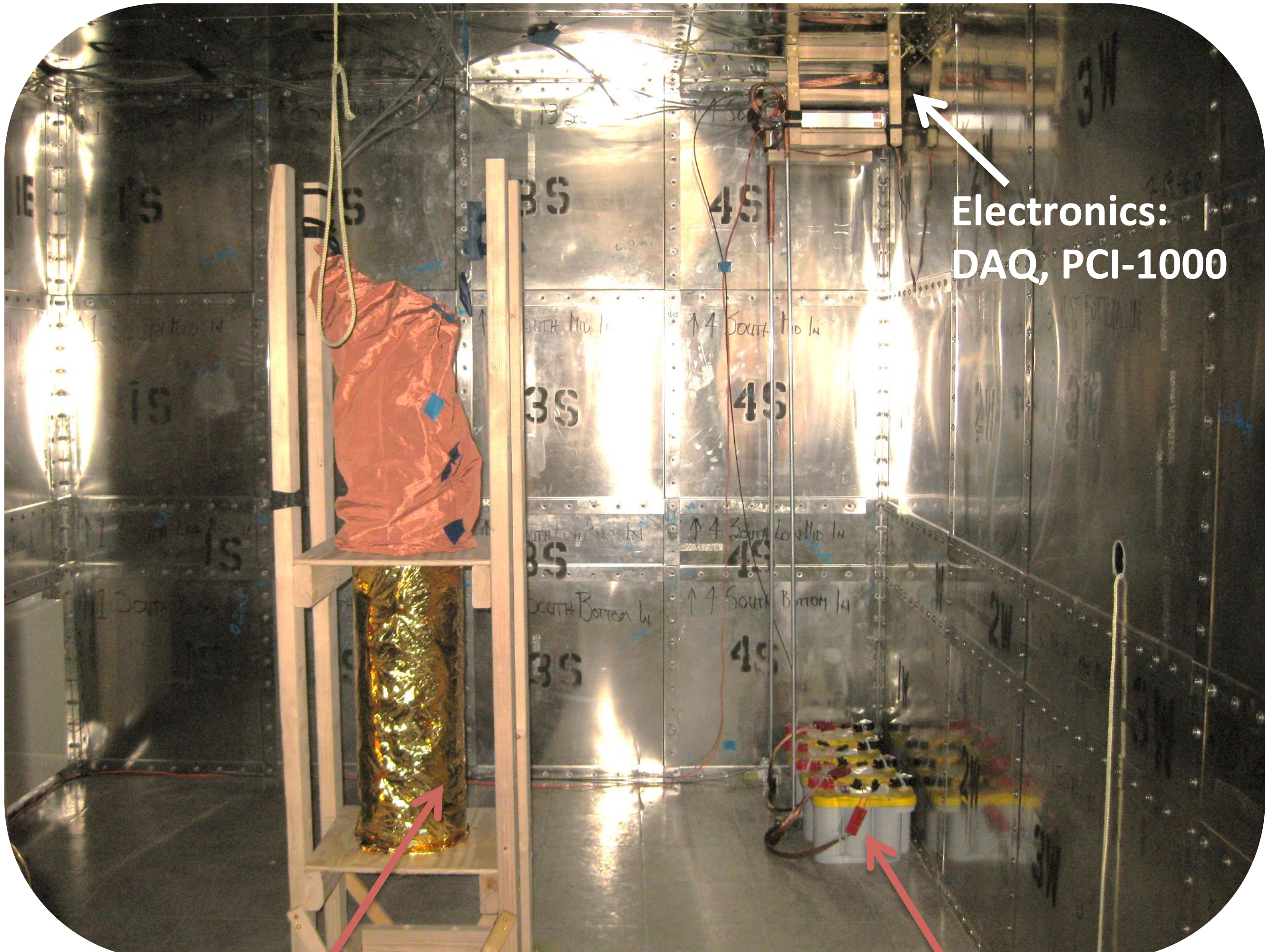
Tests have been with a prototype, large-area planar gradiometer + long leads to a high-inductance SQUID.





Setup Inside the Shielded Room



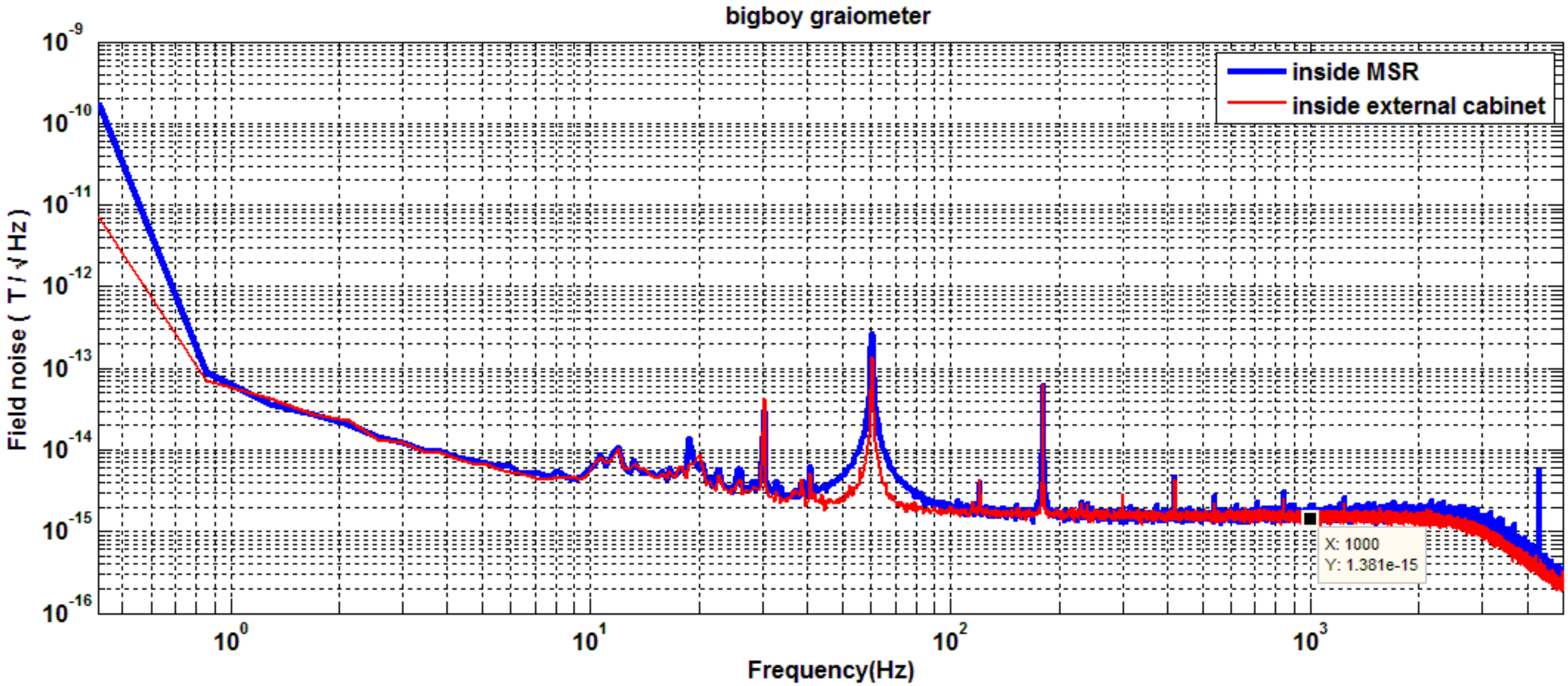


Relocation of Electronics to RF-only Shield

S.S conduit for continuous shielding.
DB-9 cables pass through the conduit

- DAQ and PCI-1000 chassis are grounded to the cabinet.
- SQUID signal reference is connected to the PCI-1000 chassis by a clip wire.
- All power wires are shielded (important).

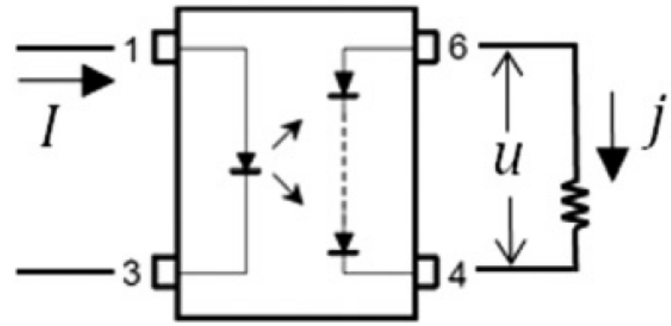
Field noise of BigBoy gradiometer

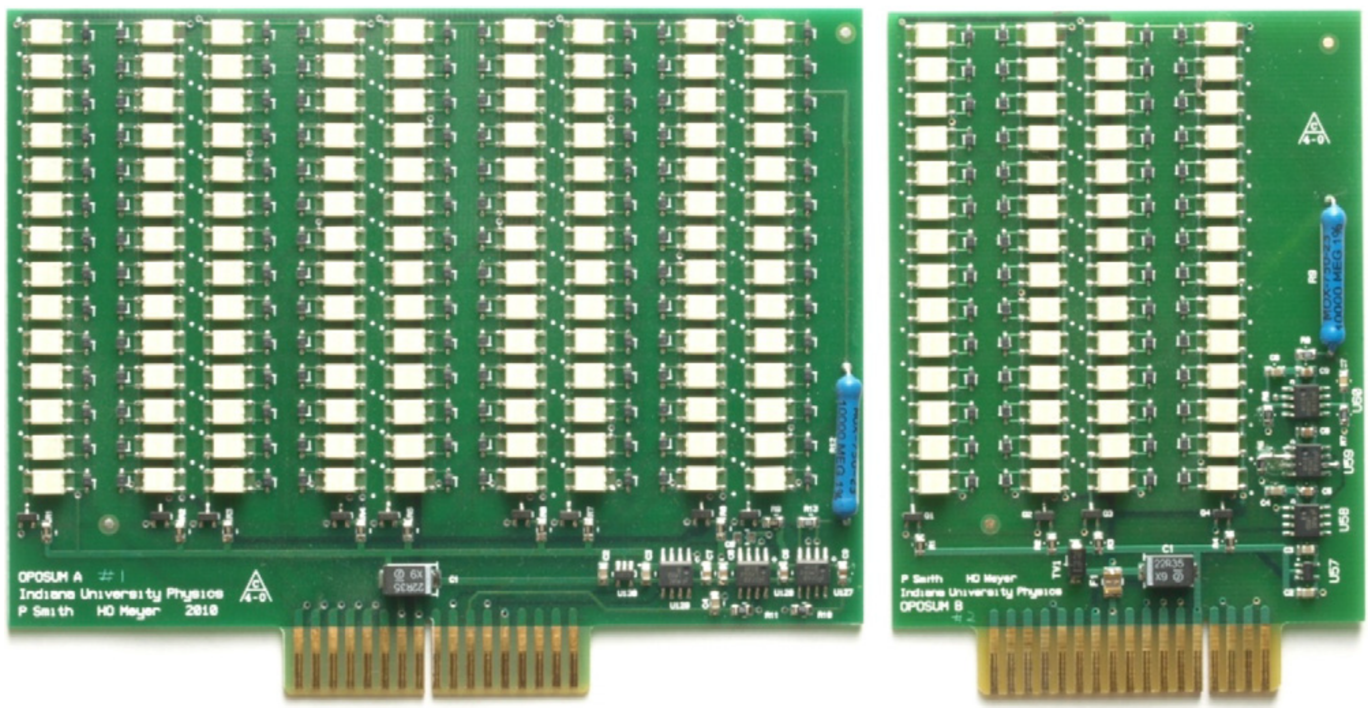


- Blue curve and red curve were measured at 4:30 pm and 9:30 pm on 11/07/13, respectively . So, the signal amplitude at 60 Hz might be changed due to the different measurement time.
- No significant change in the field noise inside MSR and external cabinet.

Low Noise, Battery-Powered PMT HV Supply

- H.O. Meyer n, P.T.Smith, “A photovoltaic high-voltage supply,” Nucl. Instrum. Meth. A **647** (2011), 117-124.
- 24VDC input, up to 2kV output with taps for individual PMT dynodes.
- Based on stacking the output of opto-isolators

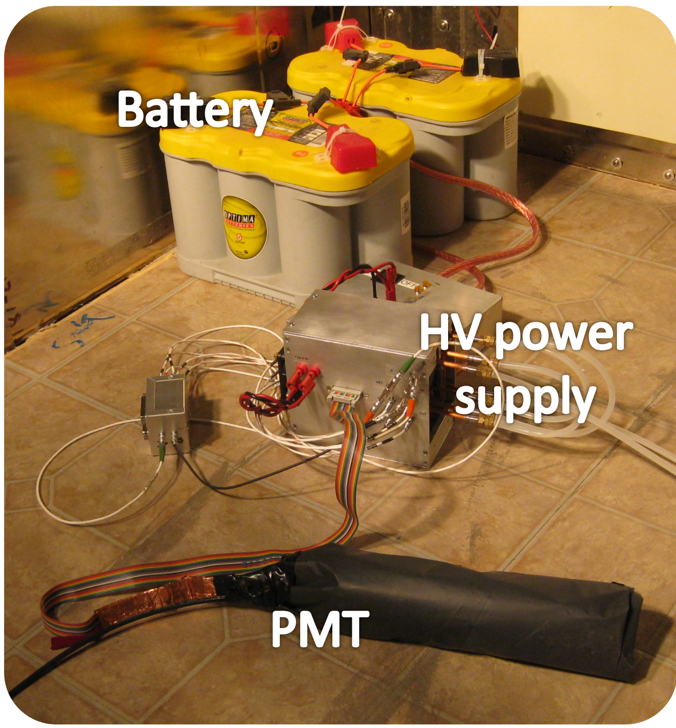


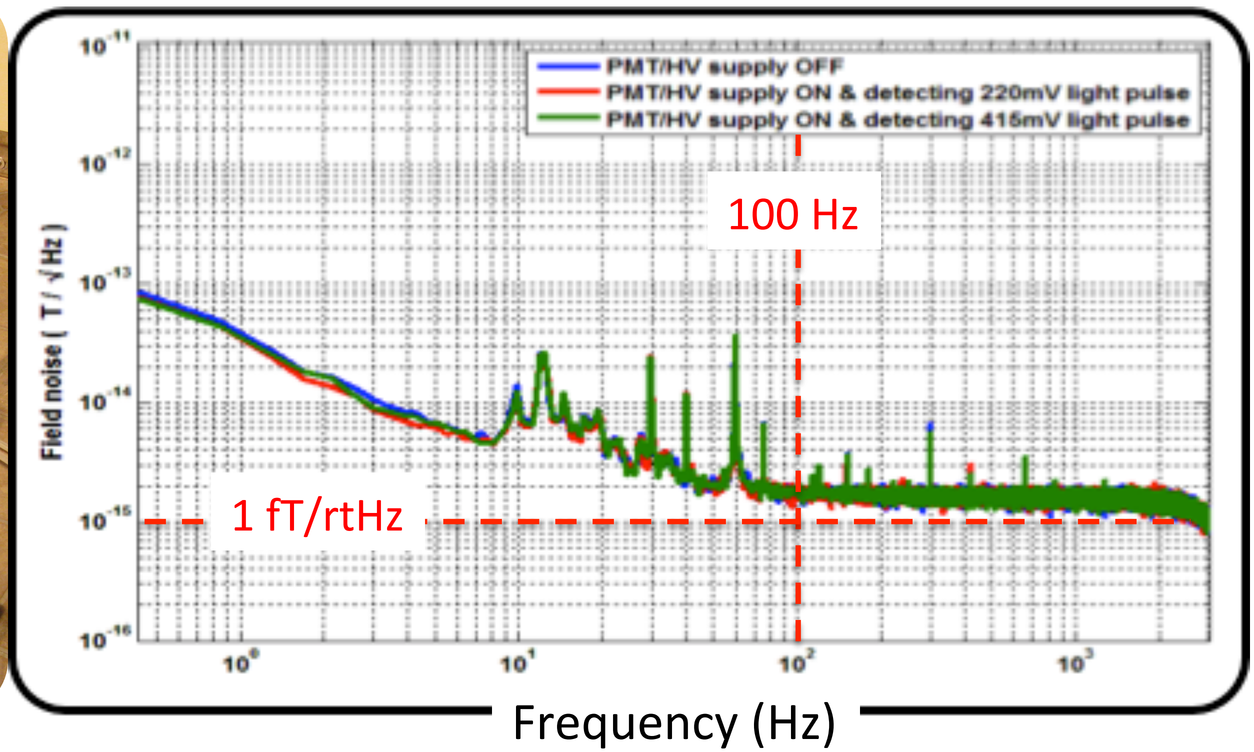


Low Noise, Battery-Powered PMT HV Supply

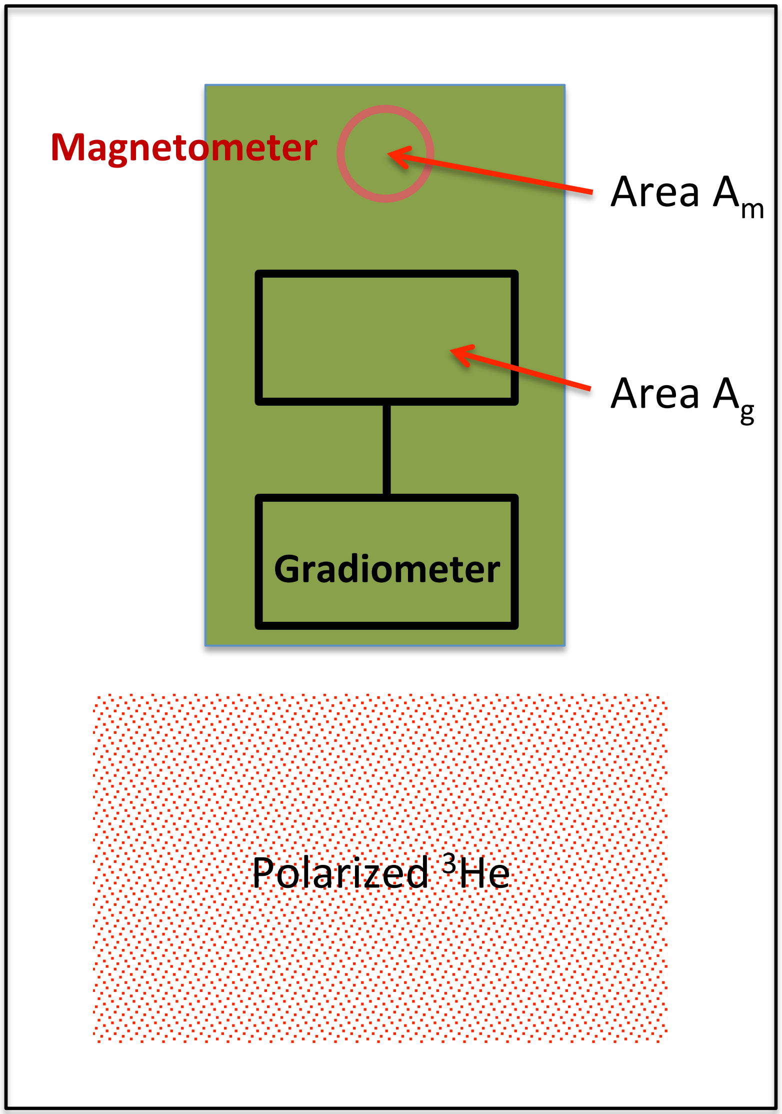
Test in the magnetically shielded room:

- SQUID gradiometer (unshielded pickup) in plastic dewar
- PMT (at room temperature) was placed in different positions and orientations, including very close to the dewar.
- No additional noise was observed due to operating the PMT.

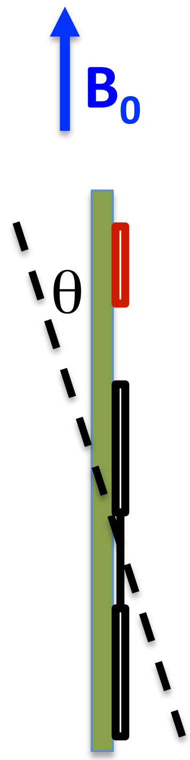




Reference Magnetometer Concept



Example: vibration out of plane of imperfectly balanced gradiometer in perfectly uniform B_0.

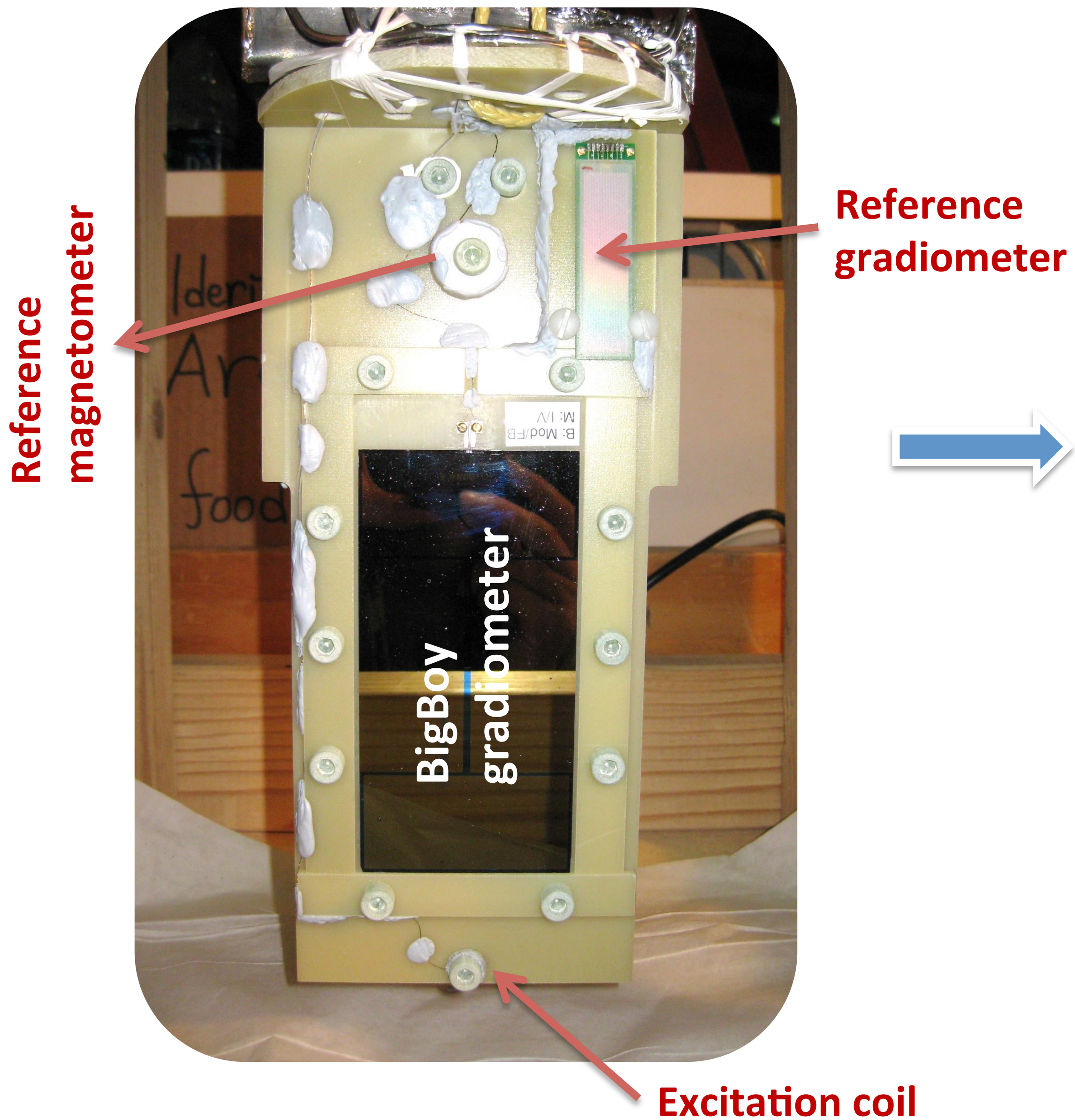


In magnetometer,
$\Phi_m(\theta) \sim B_0\, A_m \sin\theta$.

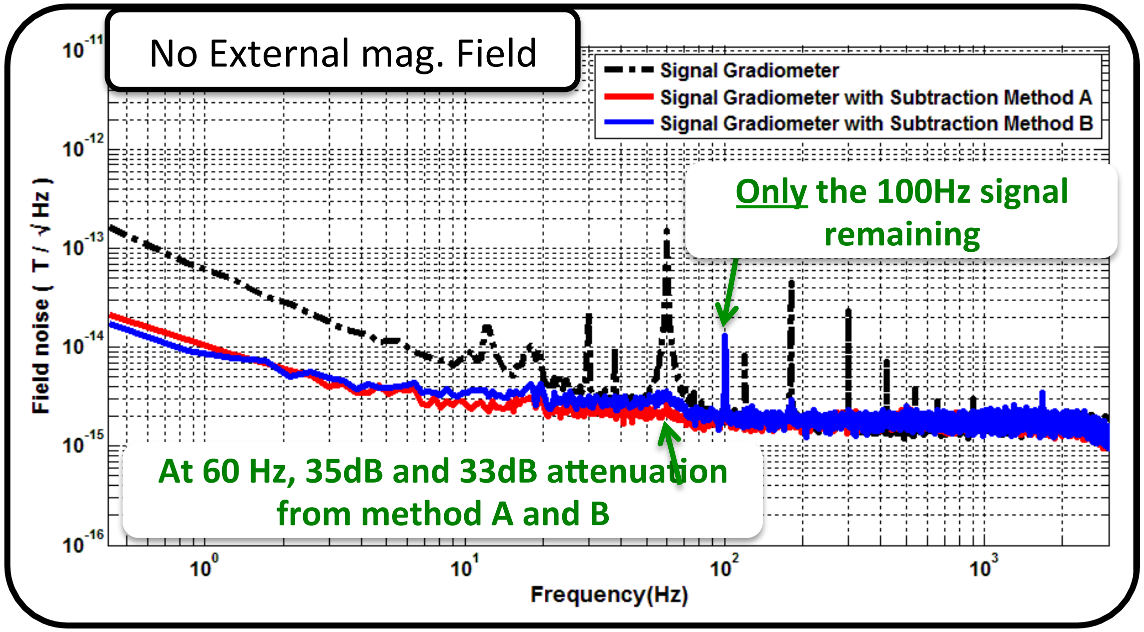
If gradiometer imbalance ε,
net flux in gradiometer pickup
$\Phi_g(\theta) \sim B_0\, A_g\, \varepsilon \sin\theta$.

For common-mode environmental signals (uniform shifts in B-field),
$\Phi_g/\Phi_m = \varepsilon\, A_g/A_m$

Reference SQUID channels

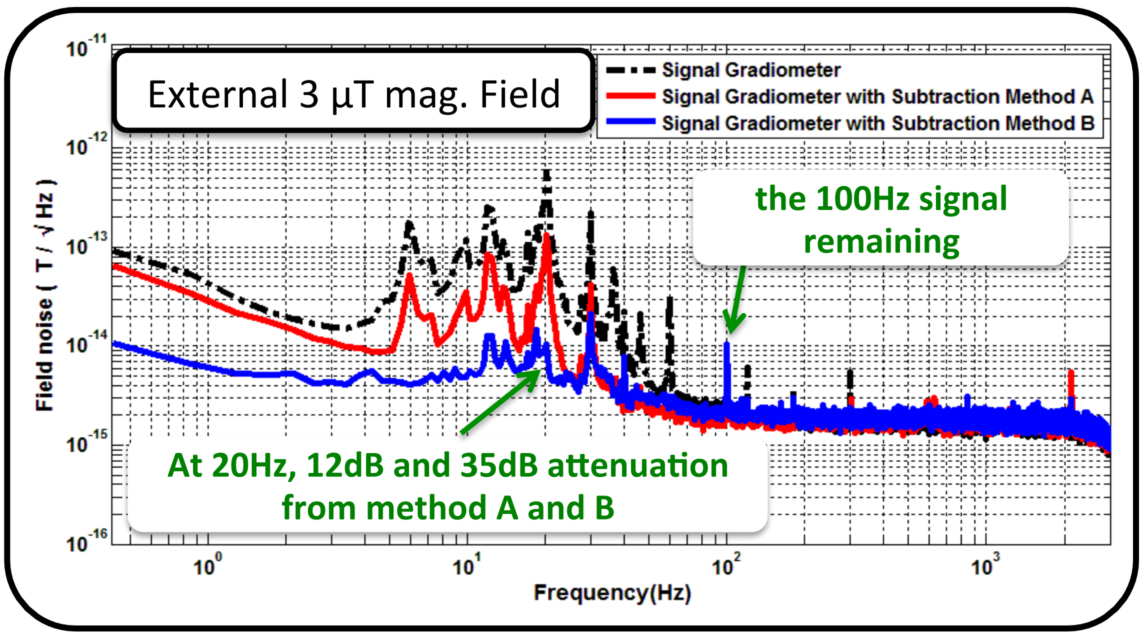


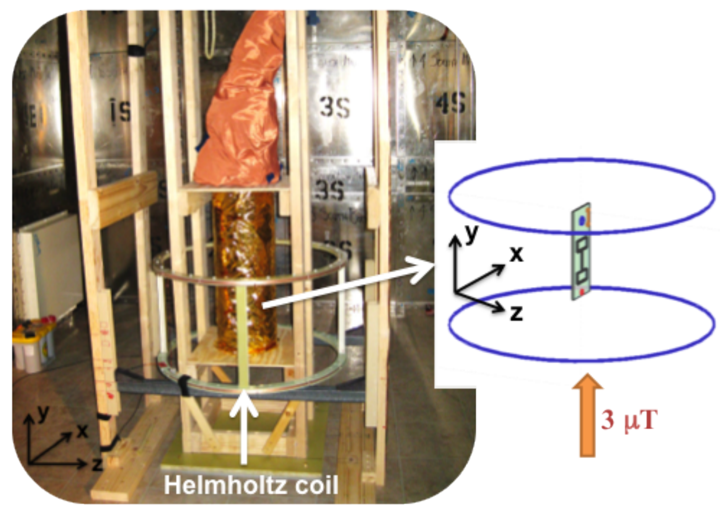
Demonstration of Noise Cancellation with a Reference Channel



The reference channel can be used to cancel out unwanted signals e.g. from vibrations or imperfect magnetic shielding.

(The reference gradiometer did not have much effect here; most of the cancellation is due to the magnetometer.)



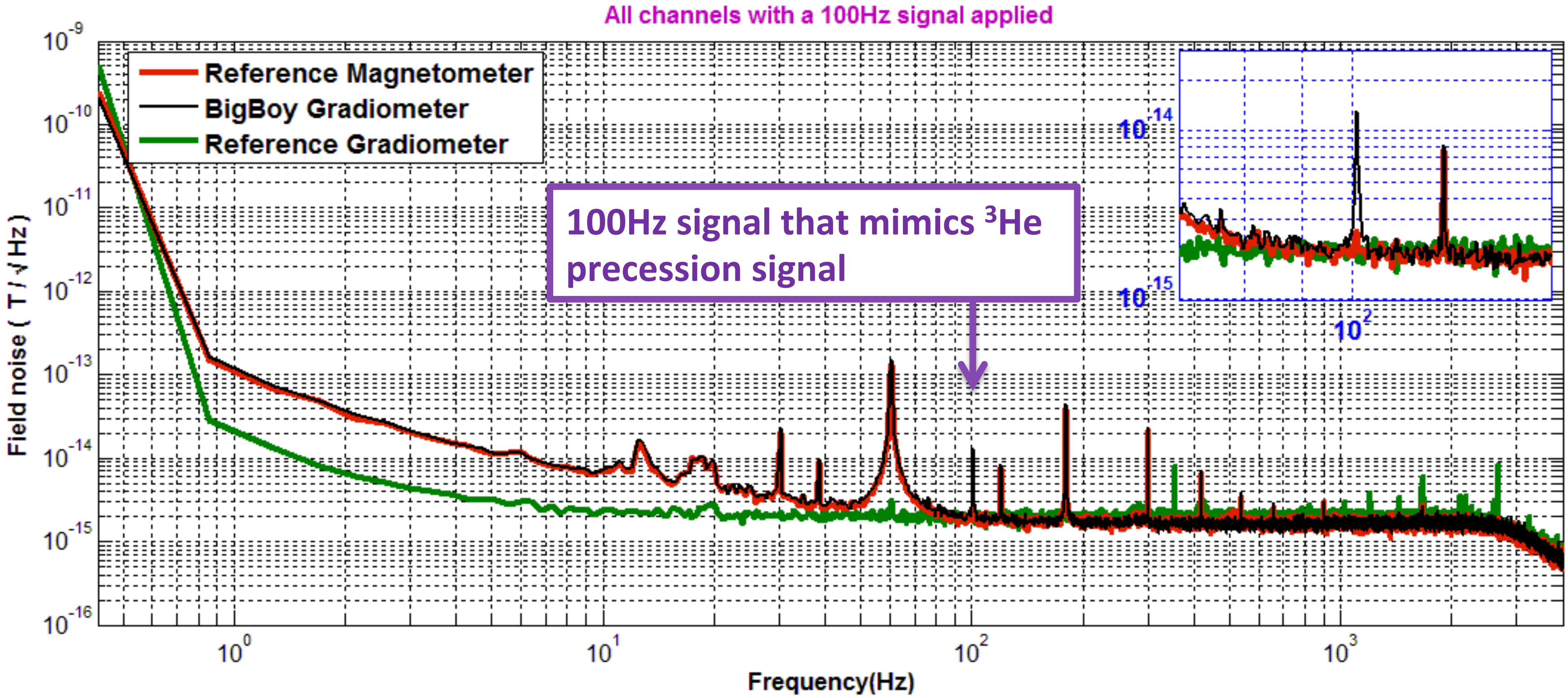


Conclusions

- A prototype SQUID system for the ^{3}He co-magnetometer readout appears to have sufficient intrinsic sensitivity, and noise measurements in a magnetically shielded room are encouraging.
- A custom PMT HV power supply seems to be compatible with low-noise SQUID operation (These are the only two devices that cannot be turned off during the measurement period.)
- Additional reference channels can enable cancellation of unwanted signals (e.g. vibration-induced).
- Battery-powering all electronics may avoid RFI problems.
- Some references on this work:
  - Sensitivity calculations: Y. J. Kim and S. M. Clayton, *IEEE Transaction on Applied Superconductivity*, Vol. 23, 2500104 (2013).
  - Summary of measurements: Y. J. Kim and S. M. Clayton, *IEEE Transaction on Applied Superconductivity,* Vol. PP, Issue 99 (2014). (Also: to appear in Superconductivity News Forum.)
- A magnetic impurity scanner using SQUIDs was not discussed…

Extra Slides

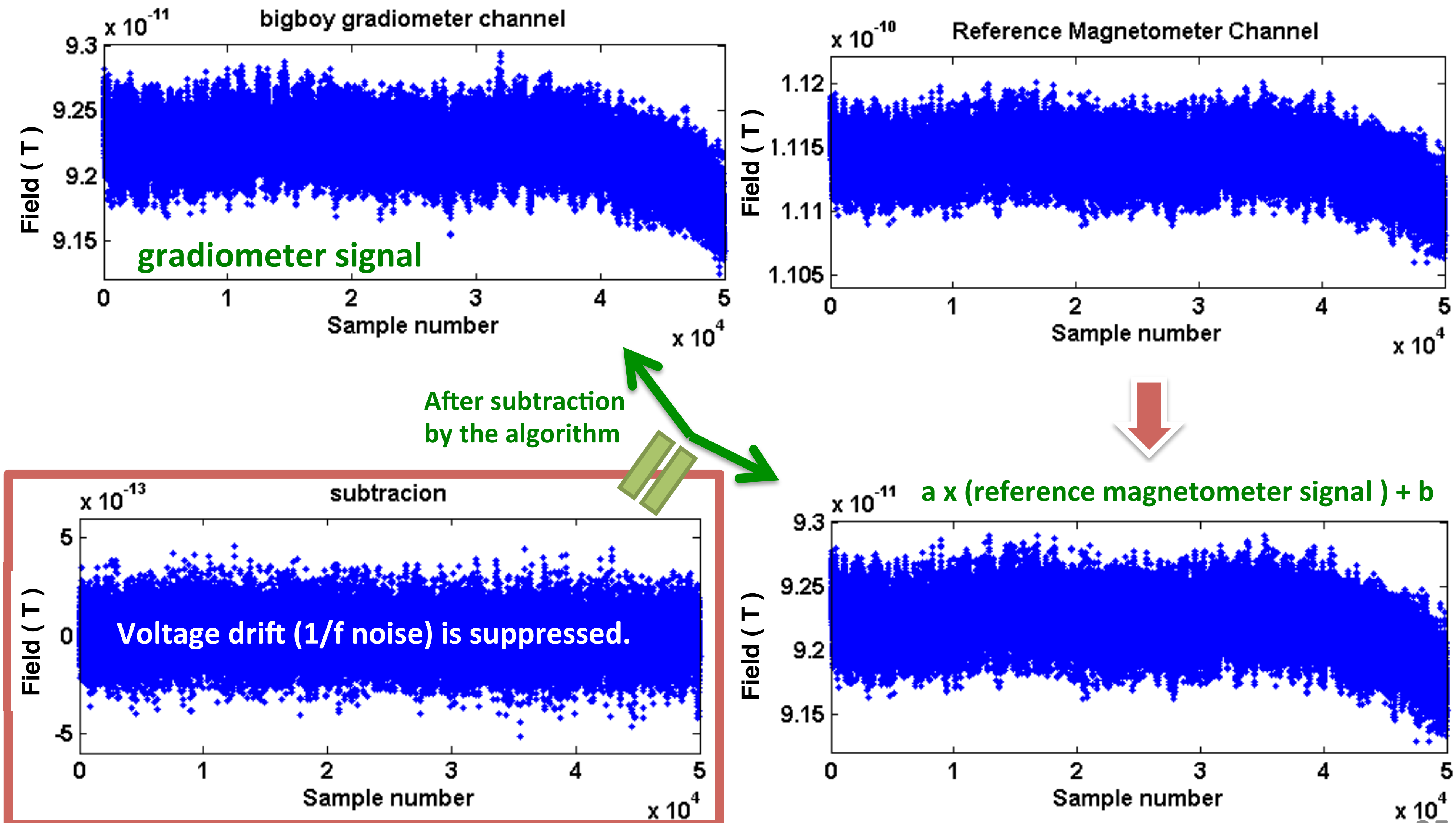
Field noise of all channels with 100 Hz signal



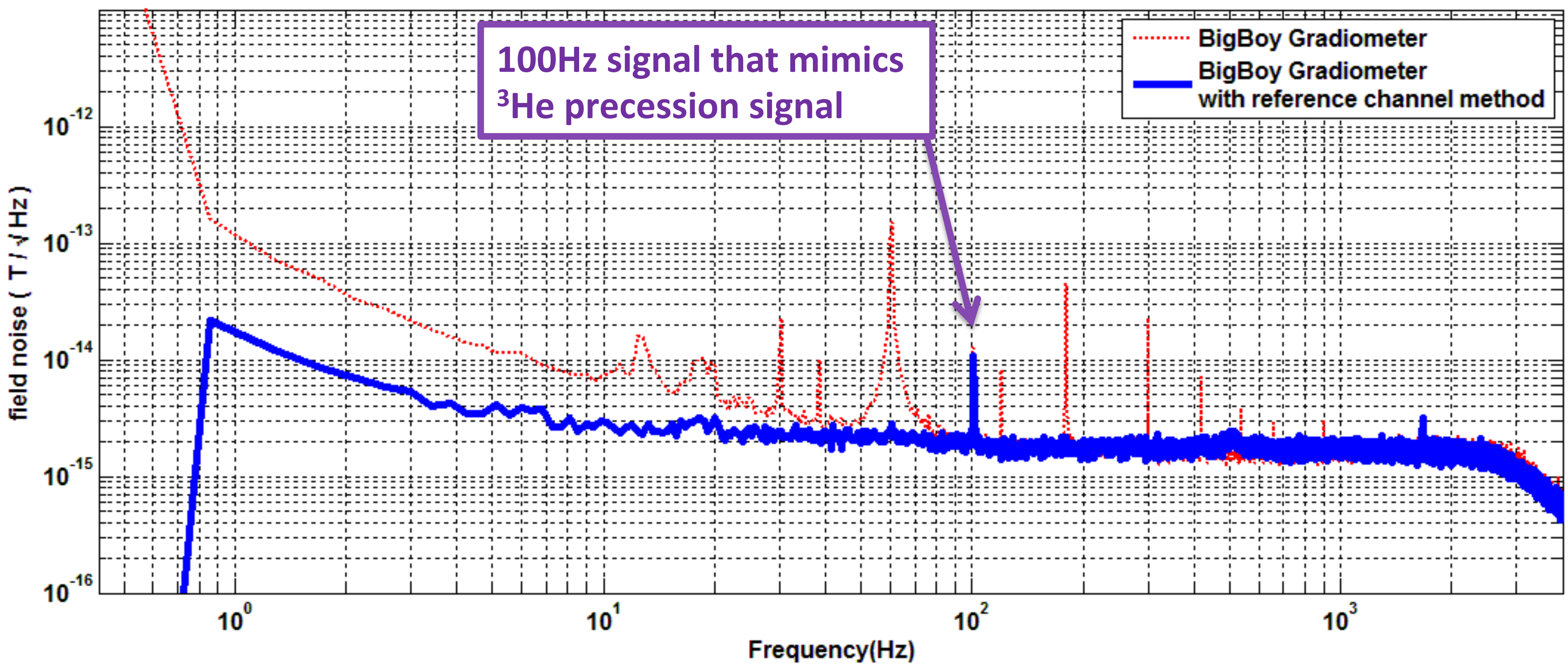
- A clean 100 Hz signal is applied to the excitation coil by an analog-optic converter to mimic the ^{3}He precession signal.
- Only the BigBoy gradiometer observes the 100 Hz signal while the reference channels don't (see the inset, an enlarged plot around 100 Hz)

Simple subtraction algorithm using only reference magnetometer

Algorithm: (gradiometer signal) – [a x (reference magnetometer signal) + b]
where a = weighting factor from the signals at 60 Hz, b = dc shift



Result with reference SQUID method



- **Conclusion:**
  1. **Field measurement on BigBoy gradiometer can be improved by the reference SQUID method!**
  2. **The reference SQUID method works well !**